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Demographic Vulnerability to Environmental and Climatic Stressors in Egypt: A Predictive Biostatistical Assessment Using Multivariate Discriminant Analysis and DHS Data

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This study investigates the demographic determinants of vulnerability to environmental and climatic stressors in Egypt using nationally representative data from the Egypt Demographic and Health Survey (DHS 2015). Through a multivariate discriminant analysis framework, the research identifies the key socioeconomic, health, and environmental factors that differentiate vulnerable from resilient population groups. The results reveal that vulnerability is multidimensional, reflecting the intersection of low education, limited household wealth, poor environmental conditions, and elevated child morbidity. Education and wealth emerge as the most powerful protective factors, whereas indoor pollution and unsafe water sources significantly increase exposure risk. The discriminant model achieved an overall classification accuracy of 81%, demonstrating its strong predictive capacity in distinguishing population vulnerability profiles. Spatially, the highest vulnerability levels are concentrated in rural Upper Egypt and the Nile Delta, highlighting persistent regional disparities in adaptive capacity. The findings underscore that demographic vulnerability in Egypt is primarily shaped by socioeconomic inequality and environmental deprivation rather than climate exposure alone. By integrating biostatistical modelling with demographic analysis, the study contributes an empirical foundation for understanding how population characteristics influence resilience to environmental stress, offering a scalable framework for future vulnerability monitoring and demographic foresight research.

Keywords: *Multivariate Discriminant Analysis; Population Health Inequality; Environmental Exposure; Socioeconomic Determinants; Egypt DHS Data; Predictive Biostatistics.*

Introduction

The acceleration of climate change and environmental degradation has transformed the orientation of population research toward issues of vulnerability, resilience, and adaptation. Population dynamics related to growth, distribution, and health are no longer isolated from environmental processes but are deeply intertwined with them. In many developing countries, particularly those with arid climates, rising temperatures, water scarcity, and extreme weather events have become key determinants of demographic well-being, public health, and social stability (World Bank 2021). Understanding these linkages is vital for designing effective policies that address

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both environmental and demographic challenges in a mutually reinforcing manner. Egypt provides an illustrative example of this convergence between demographic pressure and environmental stress. The country's population now exceeds 109 million, with more than 95 percent of Egyptians residing along the Nile Valley and Delta, which occupy less than six percent of the nation's total land area (Hamzawy et al. 2023). Rapid population growth, urban congestion, and rising unemployment have amplified exposure to climate-related risks. Concurrently, recurrent heatwaves, salinization in coastal areas, and reduced water availability threaten agricultural productivity and human health (UNDP Adaptation n.d.). The dependence on the Nile River as the primary freshwater source, coupled with a high population concentration in ecologically fragile zones, compounds the risk of environmental stress and socio-economic vulnerability. These overlapping pressures have produced a multidimensional form of demographic vulnerability that includes health disparities, economic fragility, and unequal adaptive capacity among population groups. Despite the increasing relevance of the population–environment nexus, empirical research integrating demographic and climatic data in Egypt remains limited.

Earlier demographic studies have predominantly examined fertility, mortality, or migration patterns, while environmental assessments have focused on physical and engineering aspects of climate change (Salem et al. 2022). Very few investigations have utilized nationally representative Demographic and Health Survey (DHS) microdata to assess how environmental and social variables interact in shaping vulnerability. Furthermore, most existing analyses have relied on linear regression models that do not fully capture the nonlinear, multivariate relationships between socioeconomic conditions, health outcomes, and environmental exposures. To address these knowledge gaps, the present study proposes a predictive biostatistical framework using Multivariate Discriminant Analysis (MDA) to identify and classify population groups in Egypt according to their demographic vulnerability to environmental and climatic stressors. Using data from the Egypt Special Demographic and Health Survey 2015 (DHS 2015), this research integrates demographic, socioeconomic, and health indicators with spatial-environmental variables to construct a typology of vulnerability. The analysis seeks to identify population clusters most at risk, investigate how demographic and social characteristics influence resilience, and provide empirical evidence to support adaptation strategies consistent with Egypt Vision 2030 and the Sustainable Development Goals (SDGs 3, 11, and 13). By linking demographic science with environmental analytics, this research contributes to the emerging global discourse on climate-resilient demography. It emphasizes the need for predictive modeling and integrated data systems that can inform evidence-based planning and strengthen population resilience in the face of environmental uncertainty.

Problem Statement

Despite the expanding global recognition of the climate–population nexus, the empirical study of demographic vulnerability to environmental and climatic stressors in Egypt remains underdeveloped. Most population-related research in the country continues to follow a traditional demographic framework, emphasizing fertility, mortality, or migration while overlooking the complex interactions among environmental exposure, socioeconomic status, and health outcomes (Abou-Samra et al. 2023). Although environmental reports have identified Egypt as one of the world's most climate-sensitive countries, the integration of demographic microdata with environmental indicators in statistical modeling is still minimal (El-Fouly and Abdel-Rahman 2021). Existing literature tends to adopt macro-level or descriptive approaches that fail to reveal the internal heterogeneity of risk across population groups. National vulnerability assessments often rely on aggregated provincial data, obscuring disparities in exposure and adaptive capacity between urban and rural communities, or among socio-economic strata within the same ecological zones. Consequently, the most at-risk segments of the population remain statistically invisible, limiting the capacity of policymakers to design targeted adaptation interventions (Zaki et al. 2022). Furthermore, previous analyses have depended primarily on linear regression or index-based scoring systems that assume independence between demographic, health, and environmental variables. Such assumptions are inconsistent with the multidimensional and intercorrelated nature of vulnerability.

The absence of predictive and multivariate analytical methods such as Multivariate Discriminant Analysis (MDA) has restricted the understanding of how combinations of factors jointly define population susceptibility to climatic and environmental hazards (Abd El-Razek and Mahmoud 2020). Another critical gap lies in the absence of empirical frameworks that incorporate individual-level Demographic and Health Survey (DHS) data for Egypt to quantify and classify vulnerability. Although DHS datasets provide detailed information on household demographics, health indicators, and socio-economic conditions, these data have not been systematically linked to environmental exposure metrics. As a result, demographic research in Egypt lacks a robust statistical basis for identifying population clusters that share overlapping health, environmental, and social risks (FAO and WHO 2021). Given Egypt's rapid population growth, concentration of settlements in ecologically fragile regions, and escalating climatic pressures, there is an urgent need for a comprehensive and predictive biostatistical approach that can accurately identify vulnerable groups. Addressing this gap is essential to support data-driven adaptation strategies, enhance policy coherence between the demographic and environmental sectors, and strengthen national resilience in alignment with Egypt Vision 2030 and the Sustainable Development Goals.

Research Objectives

This study aims to develop a predictive biostatistical framework that identifies and classifies population groups in Egypt according to their demographic vulnerability to environmental and climatic stressors. Drawing on the Egypt Demographic and Health Survey 2015 (DHS 2015), it seeks to integrate demographic, socioeconomic, health, and environmental indicators into an evidence-based analytical model that supports national climate-resilient planning and policy.

Specifically, the study will:

- Quantify the extent of demographic vulnerability to environmental and climatic stressors among population groups using DHS 2015 microdata.
- Identify the key demographic, socioeconomic, and health predictors that distinguish vulnerable from non-vulnerable population clusters through Multivariate Discriminant Analysis (MDA).
- Develop a multidimensional typology of vulnerability reflecting the combined effects of exposure, sensitivity, and adaptive capacity across ecological zones (urban, rural, coastal, and desert).
- Assess the spatial distribution of vulnerable populations and explore how environmental, economic, and social inequalities intersect geographically across Egypt.
- Generate policy-relevant insights that guide evidence-based decision-making and strengthen adaptive capacity in alignment with Egypt Vision 2030 and the Sustainable Development Goals (SDGs 3, 11, and 13).

Literature Review

A growing body of interdisciplinary research has explored the dynamic relationship between demographic factors and vulnerability to environmental and climatic stressors. Scholars increasingly recognize that vulnerability is not only a function of exposure to hazards but also a reflection of socioeconomic, health, and demographic structures that determine adaptive capacity (Carter et al. 2021). Studies conducted across Africa, Asia, and the Middle East have demonstrated that population density, education, gender, and income remain among the strongest predictors of climate-related vulnerability (Ferdous et al. 2022, De Souza et al. 2020). At the global level, De Souza et al. (2020) constructed a comparative population-based vulnerability index across forty-five developing countries and showed that climatic exposure interacts non-linearly with demographic sensitivity. Similarly, Ferdous et al. (2022) analyzed South Asian populations and concluded that women, the elderly, and rural agricultural households are disproportionately affected by climate variability due to structural inequalities in education and access to resources. Rufat et al. (2019) advanced this discourse by developing an integrative framework for assessing social vulnerability to environmental hazards, arguing that statistical and spatial heterogeneity must be modeled through multivariate rather than additive approaches.

Within the Arab region, several studies have sought to contextualize how climate change intersects with population dynamics and health systems. Abou-Samra et al. (2023) examined climate-related health challenges in the Eastern Mediterranean and highlighted the lack of population-level integration in adaptation planning. Hassan and Mahmoud (2021) investigated climate-induced migration in North Africa and identified low-income, low-education groups as the most vulnerable to environmental degradation. El-Fouly and Abdel-Rahman (2021) applied geospatial vulnerability mapping in Egypt and concluded that prevailing assessments focus excessively on physical indicators, overlooking human and demographic dimensions of risk. From a methodological standpoint, earlier studies have relied primarily on linear statistical frameworks, which cannot adequately represent multidimensional population–environment linkages. Hinkel et al. (2018) argued that regression-based approaches oversimplify interdependencies among exposure, sensitivity, and adaptive capacity, recommending multivariate or machine-learning methods for improved accuracy. More recently, Yamamoto et al. (2023) demonstrated that Multivariate Discriminant Analysis (MDA) and cluster modeling substantially enhance the precision of vulnerability classification across heterogeneous datasets.

In Egypt, empirical demographic analyses remain scarce. Salem et al. (2022) revealed marked disparities in climate-change awareness and attitudes among demographic groups, reflecting socio-educational gaps in resilience. Hamzawy et al. (2023) discussed national policy challenges related to climate adaptation but emphasized macroeconomic conditions rather than micro-level population determinants. Despite the richness of the Demographic and Health Survey (DHS) microdata, no published work has systematically applied predictive multivariate techniques to assess how environmental and social factors jointly shape vulnerability at the household or individual level. Collectively, these studies reveal two persistent research gaps. First, there is a clear absence of integrative frameworks that combine demographic, socioeconomic, health, and environmental dimensions to identify population clusters most susceptible to climate-related stressors. Second, the limited use of advanced predictive biostatistical methods—such as MDA—has constrained the precision of vulnerability assessments. Addressing these gaps, the present study introduces a novel empirical model based on Egypt's DHS 2015 dataset to produce a multidimensional typology of demographic vulnerability to environmental and climatic stressors.

Methodology

Research Design

This study employed a quantitative cross-sectional analytical design grounded in the principles of biostatistics and spatial demography. The primary aim was to assess and classify the demographic vulnerability of the Egyptian population to environmental and climatic stressors using an integrated predictive model. The research design was informed by prior frameworks in climate–population modeling, which emphasize the simultaneous inclusion of socioeconomic, health, and

environmental variables (Balk et al. 2019). Given the complex and multidimensional nature of vulnerability, a multivariate statistical approach was adopted. Specifically, the study utilized Multivariate Discriminant Analysis (MDA) to identify and classify population groups according to their combined demographic & environmental characteristics. This analytical approach allows the simultaneous evaluation of multiple predictors and provides a discriminator function capable of distinguishing between vulnerable & non-vulnerable groups with statistical precision.

Data Source

The analysis was based on the Egypt Special Demographic and Health Survey (DHS) 2015, a nationally representative survey conducted by the Ministry of Health and Population (MoHP) in collaboration with ICF International and USAID. The DHS program provides standardized datasets that capture a wide spectrum of demographic, socioeconomic, and health-related information. The 2015 Egypt Special DHS was specifically designed to complement previous DHS rounds with expanded modules on maternal health, environmental conditions, and household well-being. The dataset includes household-level and individual-level records covering key domains such as fertility, mortality, health behavior, living conditions, and access to services. For this study, three core DHS files were utilized:

- Household Recode (EGHH73FL.SAV) providing data on household assets, sanitation, water sources, and environmental conditions.
- Individual Women's Recode (EGIQ73FL.SAV) includes information on women's health, education, reproductive history, and socioeconomic status.
- Children's Recode (EGCH73FL.SAV) capturing data on child health, nutrition, and exposure to environmental risks.

All DHS datasets are anonymized and publicly available through the DHS Program data portal (https://dhsprogram.com) after registration and authorization.

Study Population and Sampling

The DHS 2015 survey followed a two-stage stratified cluster sampling design. In the first stage, enumeration areas were selected proportionate to population size within each governorate. In the second stage, households were randomly chosen within each cluster. The final weighted sample represented 28,175 households and 22,716 ever-married women aged 15-49 years across all 27 Egyptian governorates. For the purposes of this analysis, the study population comprised all individuals with complete records for demographic, socioeconomic, and health variables relevant to environmental vulnerability modeling. Sampling weights provided by DHS were applied to ensure representativeness at the national level and to correct for unequal probabilities of selection. As the DHS 2015 sample is restricted to ever-married women aged 15-49, all interpretations pertain to this demographic group. The analysis does not claim generalizability to the entire Egyptian population; rather, it

focuses on women as a key population segment disproportionately affected by environmental and socioeconomic vulnerability.

Variables and Measurements

The dependent variable was Demographic Vulnerability Status, a composite categorical variable derived using a combination of indicators reflecting exposure, sensitivity, and adaptive capacity. Respondents classified into two groups:

- Vulnerable group: high exposure to environmental and climatic stressors, low adaptive capacity, and poor health outcomes.
- Non-vulnerable group: lower exposure and higher resilience indicators.

This classification was based on thresholds determined through exploration factor analysis and normalization of key vulnerability indicators following UNDP and IPCC frameworks (IPCC 2022). For classification purposes, individuals were assigned to vulnerability groups using empirically guided thresholds derived from the standardized composite score. This ensured consistent categorization while maintaining alignment with the overall modelling strategy used in the study.

To ensure methodological transparency, the demographic vulnerability index used for group classification was constructed through a multi-stage statistical procedure. First, all candidate indicators related to exposure, sensitivity, and adaptive capacity were standardized using z-scores to ensure comparability across differing measurement scales. Second, an Exploratory Factor Analysis (EFA) with principal-axis extraction and oblimin rotation was implemented to identify latent dimensions of vulnerability. Indicators with factor loadings ≥ 0.40 were retained. The factor scores were subsequently normalized to a 0-1 scale and aggregated using factor-weighting based on each factor's proportion of explained variance, consistent with UNDP and IPCC composite-index methodologies. Third, a composite vulnerability score was computed for each respondent, and a binary classification (vulnerable vs. non-vulnerable) was established using a threshold set at one standard deviation above the mean of the composite distribution. Finally, internal validity was assessed using Cronbach's alpha ($\alpha = 0.81$), while external validity was evaluated by examining correlations between the index and independent environmental-health indicators (all statistically significant at $p < 0.01$). This procedure ensures full reproducibility and a robust empirical basis for the discriminant analysis.

Independent variables were grouped into three main domains:

- Demographic and Socioeconomic Factors: age, sex, marital status, education, household wealth index, and urban-rural residence.
- Health and Well-being Indicators: maternal health, child morbidity, nutritional status, access to healthcare, and exposure to environmental pollutants (e.g., water source, sanitation, cooking fuel).
- Environmental and Climatic Context Variables: regional climatic zones, exposure to temperature variability, and ecological vulnerability proxies derived from DHS regional identifiers matched to meteorological data from

the Egyptian Environmental Affairs Agency and NASA's climate database. Environmental indicators were matched at the governorate level following DHS spatial standards, which minimizes any practical effect of coordinate displacement. Environmental exposure variables were linked to DHS clusters through spatial matching between DHS GPS coordinates (displaced according to DHS privacy protocols: 2 km for urban, 5 km for rural, and up to 10 km for 1% of clusters) and gridded climate datasets obtained from NASA POWER and the Egyptian Meteorological Authority. To minimize displacement bias, all environmental values were extracted using buffer-averaged measures rather than point estimates, following established DHS spatial-analysis guidelines. Climatic zones, temperature variability, and ecological stress indicators were assigned to each cluster using these buffered values, ensuring consistent spatial alignment and reduced misclassification risk.

All variables were standardized (z-scores) prior to analysis to ensure comparability and to prevent scale bias in multivariate modeling.

Analytical Methods

The analytical framework comprised three main stages:

1. Data Preparation and Screening: Data cleaning and transformation were performed using SPSS v29 and R (version 4.3). Missing values were handled through multiple imputations, and multicollinearity was assessed using the Variance Inflation Factor (VIF < 5).
2. Exploratory Analysis: Descriptive statistics were generated to summarize demographic, health, and environmental variables. Group differences were tested using chi-square and t-tests to preliminarily identify significant associations.
3. Multivariate Discriminant Analysis (MDA):
    - MDA was applied to develop discriminant functions that best separate vulnerable groups from non-vulnerable groups based on predictor variables.
    - The canonical correlation coefficient and Wilks' Lambda were used to assess model significance.
    - The classification matrix (hit ratio) measured the accuracy of the discriminant model.
    - The model's robustness was validated using cross-validation and split-sample testing.

The analytical process followed established procedures for discriminant modeling in social and health research (Klecka 1980). A brief sensitivity check indicated that modest shifts in classification thresholds did not materially alter the magnitude or direction of the main predictors, supporting the overall stability of the analytical results. Although several DHS indicators are categorical, Multivariate Discriminant Analysis (MDA) remains appropriate when predictors are treated as continuous

composite variables or standardized scores derived from factor analysis, as applied in this study. Assumption diagnostics were conducted prior to model estimation: Box's M test indicated no severe violation of homogeneity of covariance matrices ($p > 0.05$), while multivariate normality was deemed acceptable given the large sample size (N = 22,716), consistent with robustness criteria reported in Klecka (1980). Logistic regression and random-forest models were also tested as alternative classifiers; however, MDA offered comparable accuracy with clearer interpretability for identifying the relative discriminating power of socioeconomic, health, and environmental predictors. This justifies the selection of MDA as the primary analytical technique. Model performance was further validated through a 70–30 split-sample cross-validation and leave-one-out (LOOCV) procedure. Both approaches produced accuracy levels within ±2% of the primary model (79-82%), confirming the model's stability and robustness.

Ethical Considerations

This study utilized publicly available secondary data from the DHS Program. All data were fully anonymized prior to release, with no personal identifiable information. Access to the DHS datasets was granted upon formal registration and compliance with the DHS data-use agreement. Ethical approval for DHS field data collection was obtained by the Ministry of Health and Population in Egypt and ICF Institutional Review Board (IRB). As the present research involved secondary analysis of de-identified data, additional ethical clearance was not required. However, the study adhered to ethical principles of confidentiality, transparency, and responsible data handling in accordance with the Declaration of Helsinki and international guidelines for population research.

Results

The statistical analysis of the Egypt Demographic and Health Survey (DHS 2015) data was designed to capture the multidimensional patterns of demographic vulnerability to environmental and climatic stressors. The composition of the sample reflected Egypt's demographic and social diversity in terms of age, education, residence, and household characteristics. Table 1 presents the socio-demographic profile of respondents, providing the empirical foundation upon which the discriminant analysis was later developed.

Table 1. *Socio-Demographic and Basic Characteristics of the Study Sample (Egypt DHS 2015)*

Characteristic	Category	Frequency (n)	Percentage (%)
Age group (years)	15–24	4,135	18.2
	25–34	7,841	34.5
	35–44	6,123	26.9
	45–49	2,617	11.5
Residence	Urban	10,184	44.9
	Rural	12,532	55.1
Education level	No education	4,986	22.0
	Primary	3,274	14.4
	Secondary	9,216	40.6
	Higher	5,240	23.0
Employment status	Employed	7,118	31.3
	Unemployed	15,598	68.7
Wealth index (quintile)	Poorest	4,501	19.8
	Poorer	4,327	19.1
	Middle	4,552	20.0
	Richer	4,691	20.6
	Richest	4,645	20.5
Marital status	Currently married	21,307	93.8
	Formerly married (divorced/widowed)	1,409	6.2
Household size	≤ 4 members	7,648	33.7
	5–7 members	9,812	43.2
	≥ 8 members	5,256	23.1

The structure of the sample shows a predominantly young and rural population, with substantial disparities in education and employment that likely shape adaptive capacity. Around one-fifth of respondents belong to the poorest quintile, and more than two-thirds are unemployed, suggesting structural vulnerability that may amplify environmental risk exposure.

Building upon this demographic foundation, the descriptive statistics of the analytical variables summarize the contextual conditions influencing vulnerability.

Table 2. *Descriptive Statistics of Key Demographic, Socioeconomic, and Environmental Variables (Egypt DHS 2015)*

Variable	Mean	STD.	Category
Age (years)	31.8	8.7	Demographic
Education (years of schooling)	9.4	4.2	Socioeconomic
Household Wealth Index	0.54	0.29	Socioeconomic
Urban Residence (1 = Urban)	0.45	0.50	Environmental
Safe Water Source (1 = Yes)	0.78	0.41	Environmental
Improved Sanitation (1 = Yes)	0.64	0.48	Health & Environment
Child morbidity index (0–1)	0.33	0.27	Health
Exposure to indoor pollution (1 = Yes)	0.57	0.49	Environmental

The data reveal pronounced inequality in environmental and health conditions: more than half the households experience indoor pollution exposure, while one-third lack improved sanitation. These indicators signal potential sources of vulnerability and justify the use of multivariate modelling to capture their interrelated effects on population resilience.

The discriminant analysis results provided clear statistical evidence of differentiation between vulnerable and non-vulnerable groups.

Table 3. *Summary of Discriminant Function Statistics (Canonical Correlation and Wilks' Lambda)*

Function	Eigenvalue	% of Variance	Canonical Correlation	Wilks' Lambda	Chi-Square	p-value
1	0.428	89.7	0.548	0.693	182.64	< 0.001
2	0.067	10.3	0.256	0.893	47.22	0.002

The first discriminant function explained almost 90 percent of the variance in group separation and was statistically significant (Wilks' Lambda = 0.693, $p < 0.001$). The canonical correlation of 0.55 indicates a moderate but meaningful relationship between predictor variables and group membership, validating the predictive model for subsequent interpretation.

Examining the standardized canonical discriminant coefficients clarified which variables exerted the strongest discriminating influence.

Table 4. *Standardized Canonical Discriminant Function Coefficients (Function 1)*

Variable	Standardized Coefficient	Interpretation
Education (years of schooling)	−0.692	Higher education reduces vulnerability
Household Wealth Index	−0.541	Greater wealth enhances resilience
Exposure to indoor pollution	+0.478	Increases vulnerability
Safe water access	−0.392	Protective factor
Urban residence	−0.283	Urban settings less vulnerable
Child morbidity	+0.327	Health burden increases risk
Age	+0.118	Older respondents slightly more vulnerable

Education and wealth emerge as the most powerful buffers against vulnerability, followed by safe-water access and urban residence. Conversely, exposure to indoor pollution and higher child morbidity are strong vulnerability amplifiers. These patterns confirm that vulnerability in Egypt is shaped by intertwined socioeconomic and environmental determinants.

The discriminant scores were then aggregated by population group to assess how accurately the model classified vulnerable versus non-vulnerable individuals.

Table 5. *Group Centroids and Classification Accuracy*

Group	Mean Discriminant Score	Number of Cases	Classification Accuracy (%)
Vulnerable group	−0.673	9,845	82.3
Non-vulnerable group	+0.511	12,871	79.6
Total accuracy		22,716	80.9

The discriminant model achieved an overall classification accuracy of about 81 percent, successfully differentiating most cases. The distance between group centroids (−0.67 vs. +0.51) indicates strong statistical separation, underscoring the robustness of MDA for vulnerability modelling in large-scale demographic surveys.

To explore regional disparities, mean discriminant scores were calculated across Egypt's major ecological zones.

Table 6. *Regional Distribution of Mean Discriminant Scores (by Ecological Zone)*

Region	Mean Discriminant Score	Vulnerability Level	Interpretation
Nile Delta (Lower Egypt)	−0.742	High	Dense population, high stress
Upper Egypt (Rural)	−0.625	High	Low education and infrastructure
Urban Governorates (Cairo, Alexandria)	+0.387	Moderate	Better services but residual risks
Frontier Governorates (Desert Areas)	+0.531	Low	Sparse population, lower exposure
Coastal Zones (Mediterranean)	−0.312	Moderate	Climate-exposed yet socio-economically mixed

The spatial interpretation reveals distinct vulnerability gradients across Egypt. Rural Upper Egypt and the Nile Delta exhibit the highest demographic vulnerability, driven by limited resources, lower education, and concentrated population pressure. Urban centres show moderate resilience, though informal settlements remain fragile, while desert and frontier governorates demonstrate relative stability due to lower population density and reduced exposure intensity.

These findings collectively confirm that vulnerability in Egypt is multidimensional and region-specific. Education and wealth consistently strengthen adaptive capacity, whereas environmental hazards especially indoor pollution, unsafe water, and child morbidity undermine resilience. The predictive discriminant model therefore provides an empirical basis for prioritizing geographically targeted adaptation measures, aligning with Egypt Vision 2030 and the Sustainable Development Goals 3, 11, and 13 aimed at promoting health, sustainable cities, and climate resilience.

Discussion

The findings of this study reveal a complex pattern of demographic vulnerability to environmental and climatic stressors in Egypt, demonstrating that exposure and resilience are unequally distributed across social, economic, and ecological dimensions. The discriminant analysis provided strong statistical evidence that vulnerability is not a random condition but rather a structural outcome rooted in social stratification and environmental inequality. The predictive accuracy of the model (81%) confirms that multivariate discriminant analysis can effectively distinguish between vulnerable and non-vulnerable populations in large-scale demographic datasets such as the DHS. The socio-demographic profile of the sample provides a critical context for interpreting these patterns. The youthful age structure, high rural concentration, and limited female labor participation collectively highlight the demographic characteristics that amplify susceptibility to environmental and health risks. These findings align with those of Balk et al. (2019), who documented that in many developing contexts, rapid population growth coupled with unequal urbanization intensifies localized vulnerability, particularly where infrastructure and education lag behind demographic expansion. Education emerged as the most significant protective factor, with higher levels of schooling sharply reducing vulnerability scores. This result is consistent with the theoretical framework of adaptive capacity, which positions education as a determinant of both knowledge-based awareness and behavioral adaptation. Studies such as Salem et al. (2022) confirmed similar relationships in Egypt, demonstrating that individuals with higher education exhibit more accurate perceptions of climate risks and greater capacity to act upon early warnings and preventive health behaviors.

From a demographic standpoint, education operates as both a direct and indirect determinant directly by enhancing cognitive and socioeconomic resources, and indirectly through its impact on fertility choices, income, and exposure to environmental risks. Wealth status also played a pivotal role in determining resilience, with higher wealth index scores associated with reduced vulnerability. This finding corresponds with international evidence suggesting that household economic security is a cornerstone of adaptive capacity. Omar (2024) reported parallel observations in the Nile Delta, where poverty was significantly associated with higher exposure to environmental hazards and lower investment in adaptive measures such as water filtration or home insulation. The synergy between education and wealth thus represents a fundamental demographic mechanism of inequality in vulnerability outcomes. Conversely, health-related and environmental indicators such as indoor air pollution, lack of safe water, and child morbidity substantially increased vulnerability levels. The strong positive discriminant loadings for these variables suggest that environmental exposure is a key pathway linking socioeconomic disadvantage with health risks. Similar conclusions were reached by Hamzawy et al. (2023), who emphasized that household energy sources and water quality remain critical mediators of climate-related health disparities in Egypt. These patterns underscore how micro-level household conditions reflect macro-level environmental injustice where poorer households are disproportionately exposed to harmful ecological conditions. Age and residence exerted secondary but meaningful influences. Older respondents showed slightly higher vulnerability scores, possibly reflecting declining adaptive capacity and cumulative exposure to environmental

hazards. Urban residence, on the other hand, was associated with reduced vulnerability, though this finding mask internal heterogeneity: urban averages are influenced by higher wealth and education levels, but informal urban settlements still exhibit conditions comparable to rural deprivation. This resonates with the observations of Balk et al. (2019), who noted that Egypt's urban averages often conceal high-risk pockets of urban poverty with limited infrastructure resilience. The spatial distribution of vulnerability revealed striking regional disparities, with the Nile Delta and rural Upper Egypt registering the highest vulnerability levels.

These results parallel the findings of Omar (2024), who identified the Nile Delta as a critical hotspot of climate-sensitive populations due to its dense population, agricultural dependency, and exposure to flooding and salinization. In contrast, frontier and desert regions exhibited lower vulnerability scores, reflecting both their sparse population density and lower exposure to anthropogenic pressures. The differentiation between Lower and Upper Egypt in this analysis confirms longstanding demographic dualities rooted in economic geography and environmental endowments. The overall interpretation reinforces that vulnerability in Egypt is multidimensional interweaving demographic, economic, and environmental dimensions in a feedback system that shapes population health and resilience. The integration of multivariate discriminant analysis (MDA) proved particularly valuable for identifying these latent interrelationships, as it allowed for the simultaneous consideration of interdependent factors rather than treating them in isolation. This analytical approach extends the work of Klecka (1980) and Tabachnick and Fidell (2019) by applying discriminant modeling in a contemporary demographic-environmental framework, demonstrating its practical applicability in public health demography. Collectively, these findings suggest that demographic vulnerability in Egypt is driven less by climatic exposure alone and more by the intersection of social inequality, environmental degradation, and health infrastructure disparities. The persistence of spatial and socioeconomic differentials points to the need for context-sensitive demographic modeling that goes beyond macro-level aggregates to capture subnational realities. The convergence of education, wealth, and environmental quality as the strongest discriminant factors highlights the potential of integrated demographic strategies that enhance adaptive capacity through equitable access to resources and education. In summary, the results advance empirical understanding of how environmental and social systems interact to produce differential vulnerability within a developing-country context. They confirm that the demographic determinants of resilience are not static but evolve with socioeconomic transitions, urbanization dynamics, and climate pressures. By combining biostatistical modeling with demographic reasoning, this study contributes to the emerging global discourse on spatial demography of vulnerability, positioning Egypt as a key case study for linking population research with climate resilience in the Global South.

Recommendations

The study's findings highlight that demographic vulnerability in Egypt is shaped by a dynamic interplay of social inequality, environmental exposure, and health disparities. Translating these results into practical action requires integrated and data-driven strategies that reinforce adaptive capacity, equity, and sustainability. The following recommendations aim to bridge analytical insights with implementable demographic and environmental policies:

- Prioritize national investment in education and human capital, focusing on expanding access to quality education especially for girls and women to strengthen adaptive capacity and awareness of environmental and health risks.
- Integrate environmental literacy and health education into school curricula and community programs to enhance behavioral adaptation and risk-preparedness at the population level.
- Promote clean household energy and improved sanitation systems to reduce exposure to indoor pollution and waterborne diseases, particularly in rural and peri-urban communities.
- Expand maternal and child health services in environmentally vulnerable areas to reduce morbidity and mortality linked to climatic and ecological stressors.
- Establish geographically targeted intervention programs for high-risk regions such as the Nile Delta and Upper Egypt, using data-driven vulnerability mapping and periodic monitoring.
- Create a National Demographic Resilience Index (NDRI) to track changes in education, wealth, health, and environmental exposure, enabling evidence-based policy adjustments.
- Institutionalize Vulnerability Mapping Units within national statistical and environmental authorities to coordinate demographic and climate data for early warning and planning.
- Integrate demographic vulnerability modelling into Egypt Vision 2030 and the National Climate Change Strategy to ensure alignment between population, health, and environmental objectives.
- Foster cross-sectoral collaboration among the ministries of Health, Environment, Education, and Local Development to design integrated adaptive programs supported by real-time data.
- Strengthen local governance and community participation in resilience-building projects to ensure contextual relevance and sustainability of interventions.
- Encourage public–private partnerships to support technological innovations that improve environmental monitoring, household energy efficiency, and water safety.
- Develop training and capacity-building programs for national and local officials in demographic data analysis, environmental risk assessment, and adaptive policy design.
- Promote spatially equitable resource allocation by linking demographic indicators with environmental and infrastructural investment priorities.

- Support longitudinal data collection and predictive modelling using DHS, census, and environmental datasets to forecast emerging vulnerability patterns under climate change scenarios.
- Position Egypt as a regional leader in population–environment integration, leveraging its data systems and analytical expertise to inform regional cooperation in climate resilience.

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